2. Inventory and Analysis Methodology

The Department of Water Resources (DWR) develops and maintains the Integrated Water Flow Model (IWFM). IWFM is a surface-subsurface hydrologic model that couples the integrated hydrologic modeling approach with a root zone component that uses the irrigation-scheduling-type approach. The stand-alone root zone modeling tool is named the IWFM Demand Calculator (IDC) which solves the soil moisture balance in the root zone to compute agricultural and urban water demands (DWR 2015). Inputs developed for the Butte Basin Groundwater Model (BBGM) and Water Inventory & Analysis (WI&A) update serve as inputs for the IWFM and IDC versions of the BBGM. Water Budgets presented in Section 5 of this report are derived from IDC results and other developed inputs as described in the following sections.

2.1 Summary of a Water Budget

The irrigation scheduling approach of IDC simulates the ways water moves into, through, and out of the root zone. Overall, just like a checking account, the inflows minus the outflows must add up to the total change in storage of water within the defined region. Water budgets can be defined for different subsets of the system. Presented in this report are water budget results for the land surface system. As shown in Figure 2.1, the inflows include precipitation (P), applied water (A_W) (i.e. irrigation), and reuse (U), and the outflows include evapotranspiration (ET), runoff (R_p), return flow (R_f), and deep percolation (D). By developing annual water budgets, we can see how each of these components changes over time as water supplies and demands change.

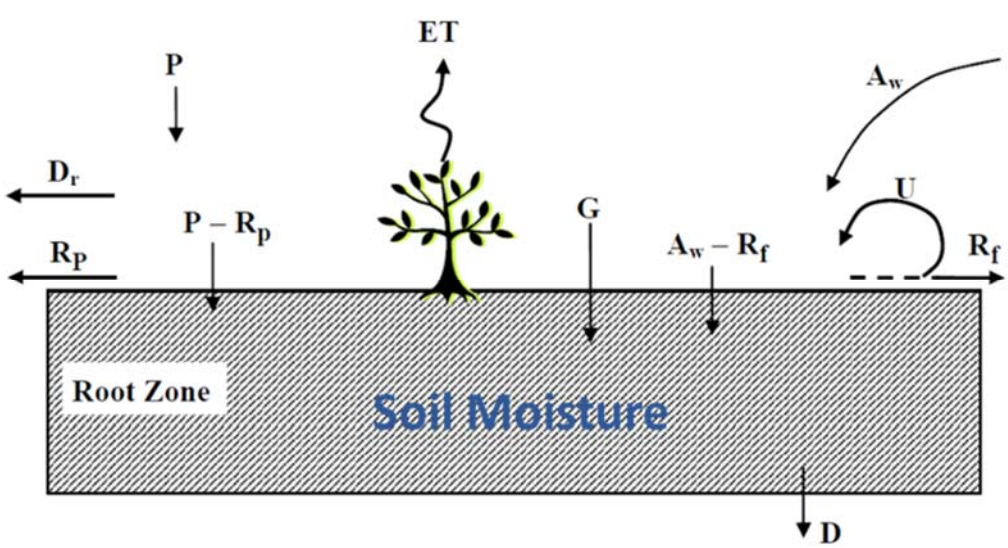

Figure 2.1. Representation of Root Zone Flow Processes by IDC (DWR 2015) (P = Precipitation, ET = Evapotranspiration, A_w = Applied Water, U = Reuse, R_f = Irrigation Return Flow, D_r = Outflow from Rice and Wetland Pond Drainage, R_p = Runoff of Precipitation, D = Deep Percolation, and G = Generic Water Source (e.g. Fog)).

To develop a water budget, both an understanding of how the system works and datasets for each of the variables are needed. Most variables are not constant and change seasonally, annually, and over a long period of time. Some of the changes are temporary (e.g. drought years), but others may be longer term or permanent (e.g. land use).

Relatively direct measurements are available for some datasets (e.g. precipitation), but for other datasets it is necessary to develop reasonable estimates based on available information. Applied water, or irrigation water demand, is calculated by the IDC component of the BBGM based on climate conditions, soil parameters, crop evapotranspiration, and irrigation practices. The source of applied water can be surface water deliveries (which are specified based on measured or estimated data) or groundwater pumping. Groundwater pumping for agricultural water use is not metered or directly measured systematically in Butte County. As a result, pumping is estimated by estimating required agricultural water demands to irrigate a particular crop. Since some of the demand may be met by delivered or recovered surface water, any remaining water requirement is assumed to be met by groundwater pumping.

Deep percolation is also calculated by IDC and represents water that moves through and drains out of the root zone. This process is driven by the characteristics of the soil as represented by specified soil parameters in IDC, particularly saturated hydraulic conductivity. This water may continue to move downward through the unsaturated zone into the aquifer system or in cases where there is a shallow or perched water table, it could move laterally into a stream channel or canal and become surface runoff or it could be utilized by phreatophytic vegetation and transpired.

Similarly, runoff is calculated by IDC and results from the intensity of precipitation events and applied water and the characteristics of the land surface as represented by NRCS curve numbers. Curve numbers are assigned based on soil properties and land use.

Methods for developing data inputs for precipitation, evapotranspiration, and other components of the system are described in Section 2.3.

2.2 Butte Basin Groundwater Model

Development of the original Butte Basin Groundwater Model (BBGM) began in 1992 by HCI under the direction and funding of the Butte Basin Water Users Association (HCI 1996). The original version used a modeling code called FEMFLOW3D and simulated historical conditions from 1970 to 1991. The model was then extended to simulate historical conditions through 1999 through a series of updates. During 2003-2008, CDM conducted a significant update to the model, changing the modeling code to IWFM v.2.4.1, revising the hydrostratigraphy from three layers to nine layers based on DWR Northern Region Office (DWR NRO) geologic cross sections, and expanding the model domain into the foothill area to directly incorporate potential recharge areas. The model was recalibrated and used to run a base case and 50% surface water curtailment scenario (CDM 2008b). This version of the BBGM is referred to as the 2008 CDM version.

The update of the BBGM for the WI&A (BBGM-2016) uses the same model domain, grid, subregions, and stream network as the 2008 CDM version (CDM 2008a) (Figure 2.2). The BBGM-2016 version runs using model code IWFM-2015 and version 2015.0.36 of the IWFM Demand Calculator (IDC) using v. 4.0 of the root zone component (DWR 2015). It maintains a daily time step with some daily input (i.e. precipitation, stream inflow), some monthly input data (i.e. surface water diversions) and some annual input data (i.e. land use). The BBGM-2016 model time period is 1970-2014.

Although model structure is the same in many ways as the 2008 CDM version, major differences include additional crop types to better represent ponded crops (i.e. rice and wetlands), recalibrated soil parameters, and elemental land use. A major change in the rootzone v.4.0 code is representation of land use on the elemental scale rather than the subregion scale and direct representation of flooding fields for ponded crops (i.e. rice and wetlands). These changes to the BBGM are described in more detail below.

2.2.1 Modeled Crops and Land Uses

Crops that require flooding are referred to as 'ponded crops' in IWFM. These include rice and managed wetlands. Rice is divided into two crop types in the BBGM. One that represents acreage with winter flooding for rice straw decomposition and the other without winter flooding for decomposition. To represent the shift in practice from rice straw burning to winter flooding for decomposition between 1991 and 2001 as a result of the Connelly-Areias-Chandler Rice Straw Burning Reduction Act of 1991, land use acreage for these crop types are shifted linearly over time from 1991 to 2001, with approximately 12 percent of rice being flooded in the winter prior to 1991 and 53 percent of rice flooded in the winter in 2001 and later years.

In Butte County, the distribution of ponded crop acreage is largely driven by and constrained by soil characteristics and the drainage properties of the soil. Thus, rice and managed wetlands acreage tend to historically be geographically stationary. In the BBGM, elements corresponding to this ponded crop acreage are identified as 'ponded crop elements' and as a result are assigned different soil properties than 'nonponded elements' with similar soil types (described in further detail in the following section). This however results in rice and wetland acreage that inevitably occurs in nonponded elements on the margins of the ponded crop element zones. This acreage is input to the BBGM as nonponded acreage for rice and managed wetlands. Acreage for all other crop types including truck crops, orchard crops, and annual crops are considered nonponded crop acreage. Native crop types, native and riparian, is specified land use acreage that does not receive applied water. Urban areas are represented by an urban crop type. Ponded and nonponded elements are shown in Figure 2.3.

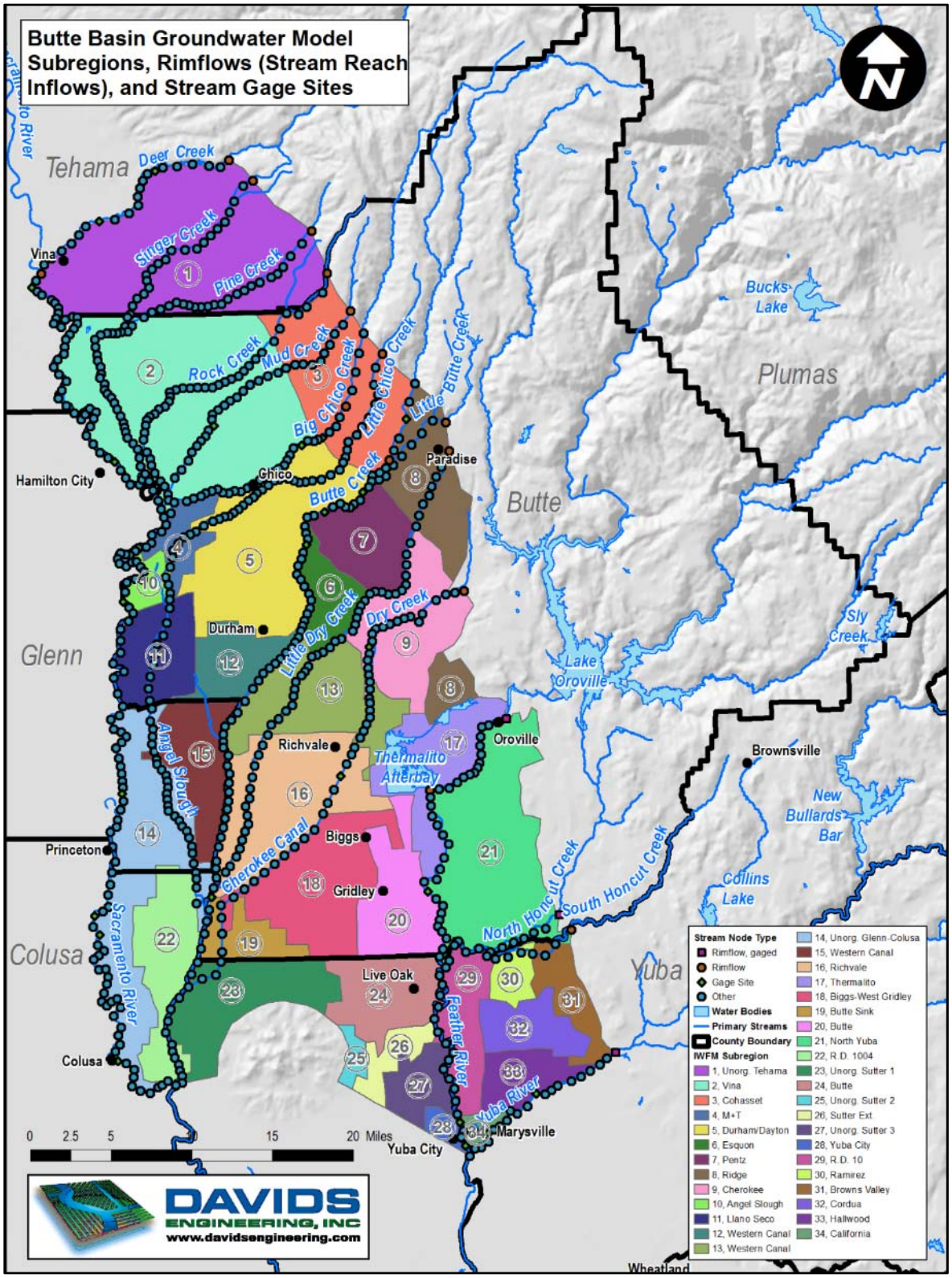

Figure 2.2. Butte Basin Groundwater Model Domain, Subregions, and Stream Network[1].

[1] The model grid is shown later in Figure 2.3.

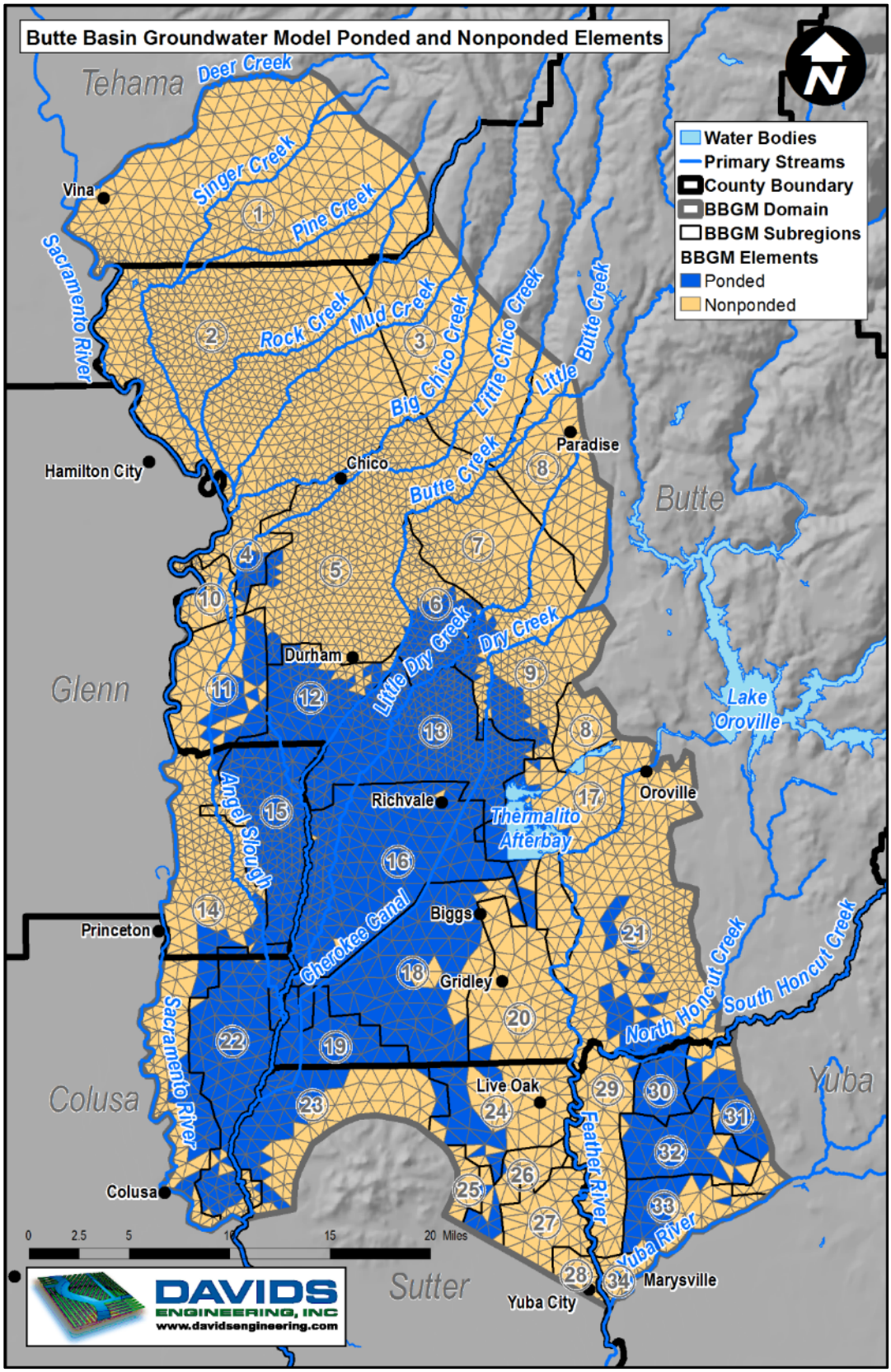

Figure 2.3. Butte Basin Groundwater Model Ponded and Nonponded Grid Elements.

For each ponded crop, a daily time series of ponding depth (in inches) is developed to represent the pattern of flood up and drainage associated with planting and harvest or wetlands management. The timing of ponding for rice is based on the timing of diversions from the Afterbay that provide the surface water source for the water district areas. For wetlands, the timing of ponding is based on refuge water management plans (CDFW 2011, USFWS 2011).

Due to laser leveling practices of rice fields that began in the 1980s and became the dominant management practice by 1995 (Mutters 2015), less water was needed to flood a more uniform field. To capture the effect of this management practice on water use, ponding depth inputs were increased going back to 1970 by a factor of two and then ramped down linearly from 1980-1995 to the current values. Current ponding depths range from 0 to about 5.5 inches and vary in time.

A schematic showing modelled crops and other land uses by category is provided in Figure 2.4.

2.2.2 Root Zone and Land Surface Parameters

Root zone and land surface parameters are assigned to each element in the BBGM. Root zone parameters describing the soil characteristics include total porosity, field capacity, wilting point, pore size distribution index, and saturated hydraulic conductivity. Campbell's equation is used to represent the moisture content in the root zone as a function of the hydraulic conductivity. Each model element is assigned a soil group based on soil texture (e.g. silty clay, sandy loam, clay loam, etc.) as specified by the NRCS soil survey. Then each soil group has a set of corresponding soil parameters. These were calibrated based on the time required to drain from saturation to field capacity[2] and the gravimetric drainage rate once field capacity is reached, which should be near zero. For elements specified as ponded elements, the saturated hydraulic conductivity is significantly reduced to avoid unreasonably high applied water estimates due to high deep percolation rates. Reduced hydraulic conductivity in these areas reflects reduced percolation resulting from heavy, clay soils; plow pan; cemented layers; and perched shallow groundwater.

A map showing soil texture class by element is included as Figure 2.5. Saturated hydraulic conductivity, reflecting soil texture class and ponded/nonponded element assignment is included as Figure 2.6.

[2] Lighter textured soils such as sands and loams are expected to drain more quickly than silts and clays.

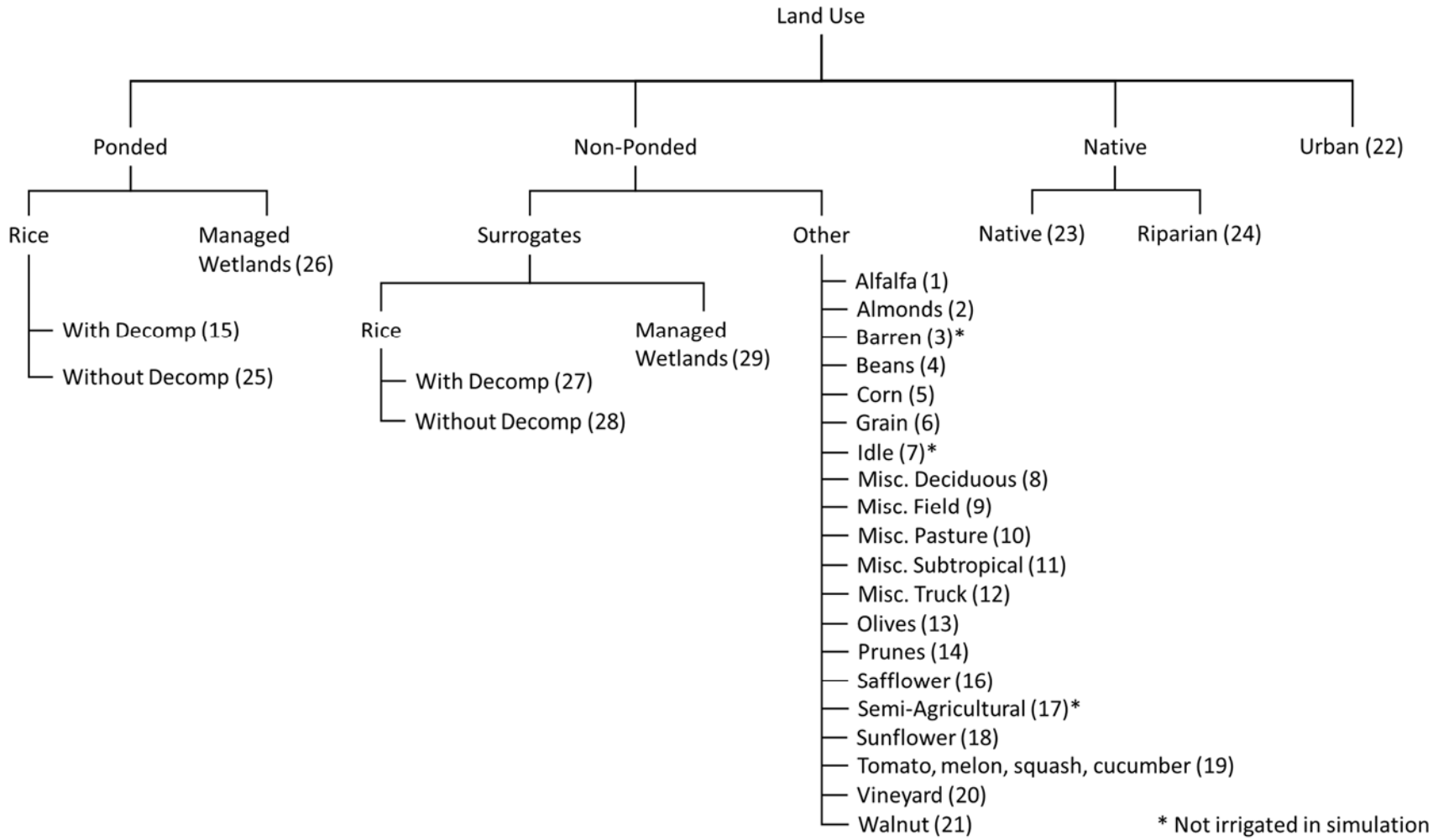

Figure 2.4. Butte Basin Groundwater Model Modelled Crops and Other Land Uses.

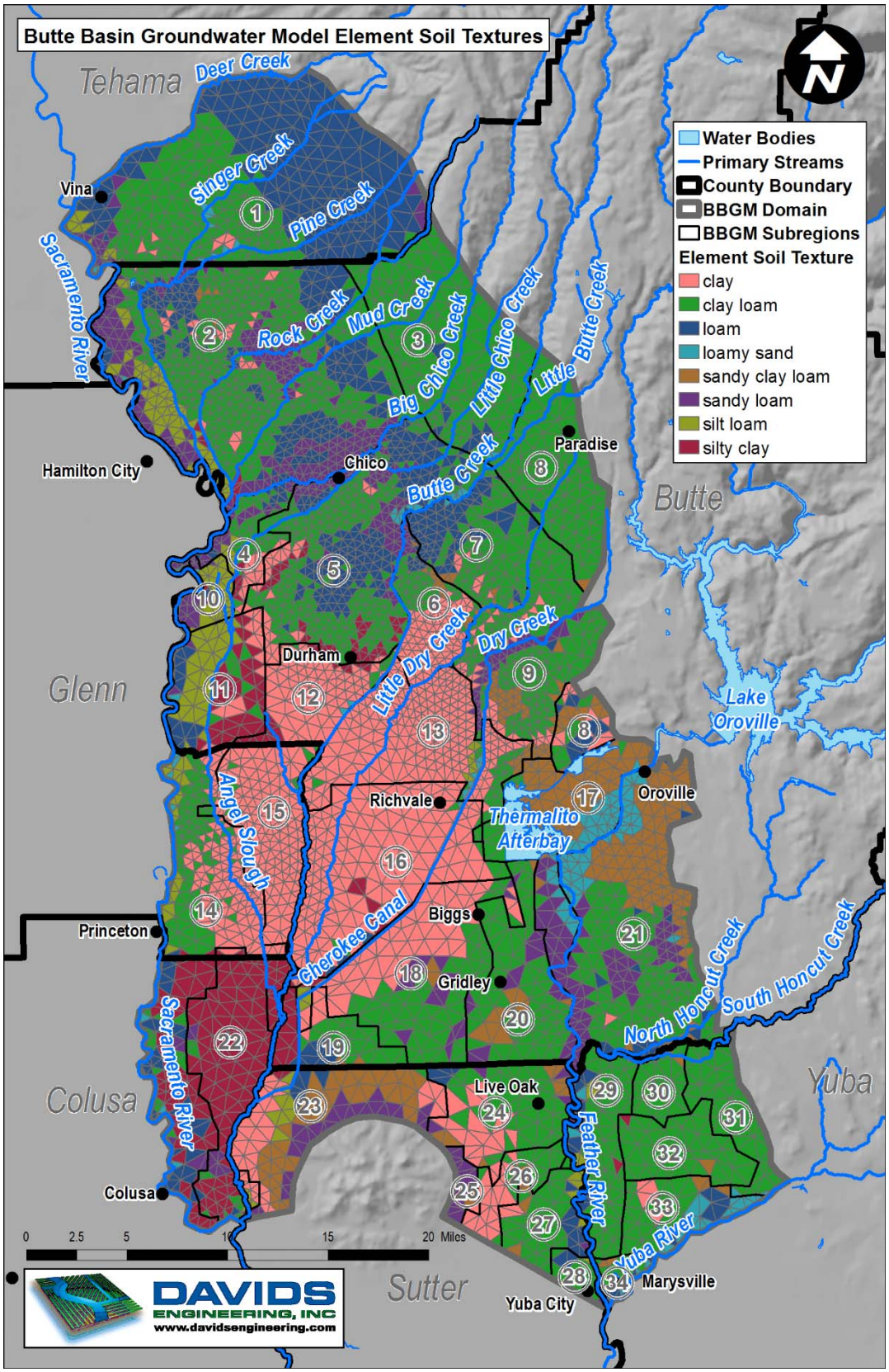

Figure 2.5. Butte Basin Groundwater Model Element Soil Textures.

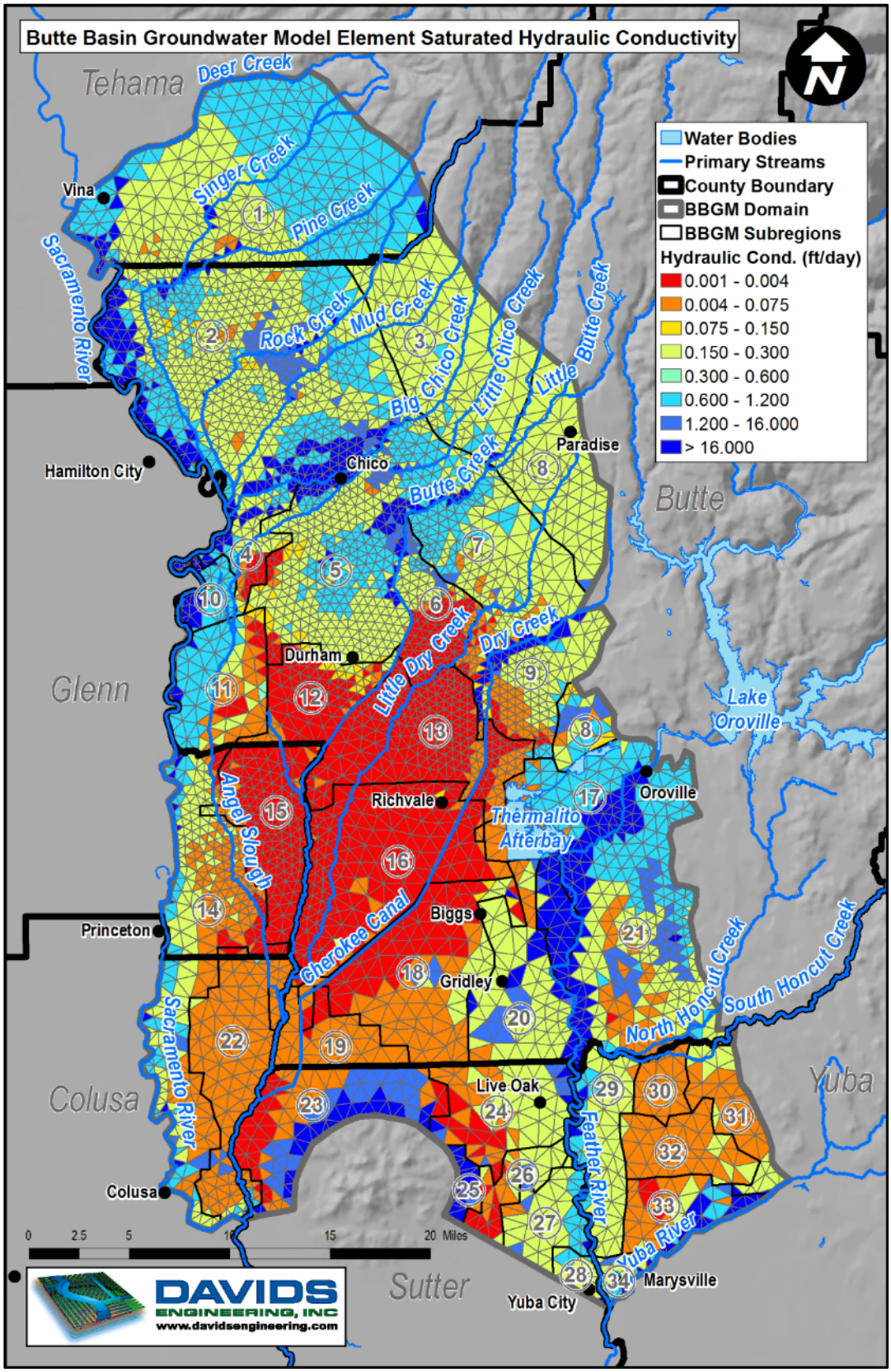

Figure 2.6. Butte Basin Groundwater Model Element Saturated Hydraulic Conductivity.

2.3 Water Inventory Methodology

This section describes methodologies for the update of the Water Inventory and Analysis Report (WI&A) and the Butte Basin Groundwater Model (BBGM) to update water supply and demand conditions through 2014. Discussion and methodologies are provided for the following datasets used in the update:

- Precipitation
- Streamflows
- Diversions and Pumping
- Land Use
- Reference Evapotranspiration (ETo), Crop Coefficients, and Actual Evapotranspiration (ETa)
- Irrigation Efficiency
- Land Surface Water Budgets

Update of the WI&A has been supported by detailed water balance analyses conducted as part of development of the Feather River Regional Agricultural Water Management Plan (FRRAWMP) (NCWA 2014). The FRRAWMP study area extends from the Sacramento River and Sutter Bypass in the west to the Feather River in the east and from Western Canal Water District in the north to Freemont Weir in the south, covering the southern portion of Butte County in the East Butte and West Butte inventory units (and subbasins). In particular, the FRRAWMP includes detailed water budgets for the Biggs-West Gridley, Butte, Richvale, and Western Canal subinventory units. An objective of the coordination of these efforts is to ensure that the most current understanding of surface water and groundwater hydrology and conditions within the County is incorporated into the WI&A.

2.3.1 Precipitation

Existing BBGM input data files of precipitation for the five weather stations represented in the model (Chico University Farm, Colusa 2 SSW, Marysville, Oroville, and Paradise) as described by CDM (2008a) were compared to raw precipitation data compiled by BCDWRC. The data were downloaded from the National Climatic Data Center (NCDC)[3]. The station locations are shown in Figure 2.7. The figure indicates the zone represented by each station, along with precipitation adjustment factors applied to estimate precipitation for each element based on long term spatial distribution of precipitation as described by CDM (2008a).

Review and update of the existing BBGM datasets included filling of gaps in both the raw data and the existing BBGM input files to ensure a complete record of precipitation for each station. Gaps for a given station were filled based on correlation to neighboring stations. Extreme daily

[3] Available at www.ncdc.noaa.gov.

precipitation totals were screened for and corrected where appropriate based on correlations to other nearby stations.

2.3.2 Streamflows

Seventeen streams are represented in the Butte Basin Groundwater Model and therefore require development of time series of inflow where these streams enter the model domain (referred to as "rimflows" or rim inflows). Major streamflows into and on the borders of the County are estimated based on U.S. Geological Survey (USGS) and California Data Exchange Center (CDEC) stream gages. These include Deer Creek, Big Chico Creek, the Upper Feather River, the Yuba River, and the Sacramento River. The majority of remaining stream inflows are estimated based on a multiplier applied to the "Big Chico Creek near Chico" gaged streamflow. A summary of the data source for each stream inflow is included in the Rimflows section of the technical memorandum *Recommended Methodologies for Update of Butte County Water Inventory and Analysis and Butte Basin Groundwater Model* (Davids Engineering 2013). This method is the same approach used in previous versions of the BBGM.

In addition to providing a summary of streamflows for major gages, an inventory of historical and existing stream gages in the County has been developed and is provided in Appendix B. BBGM rimflow locations and associated stream gages were shown previously in Figure 2.2.

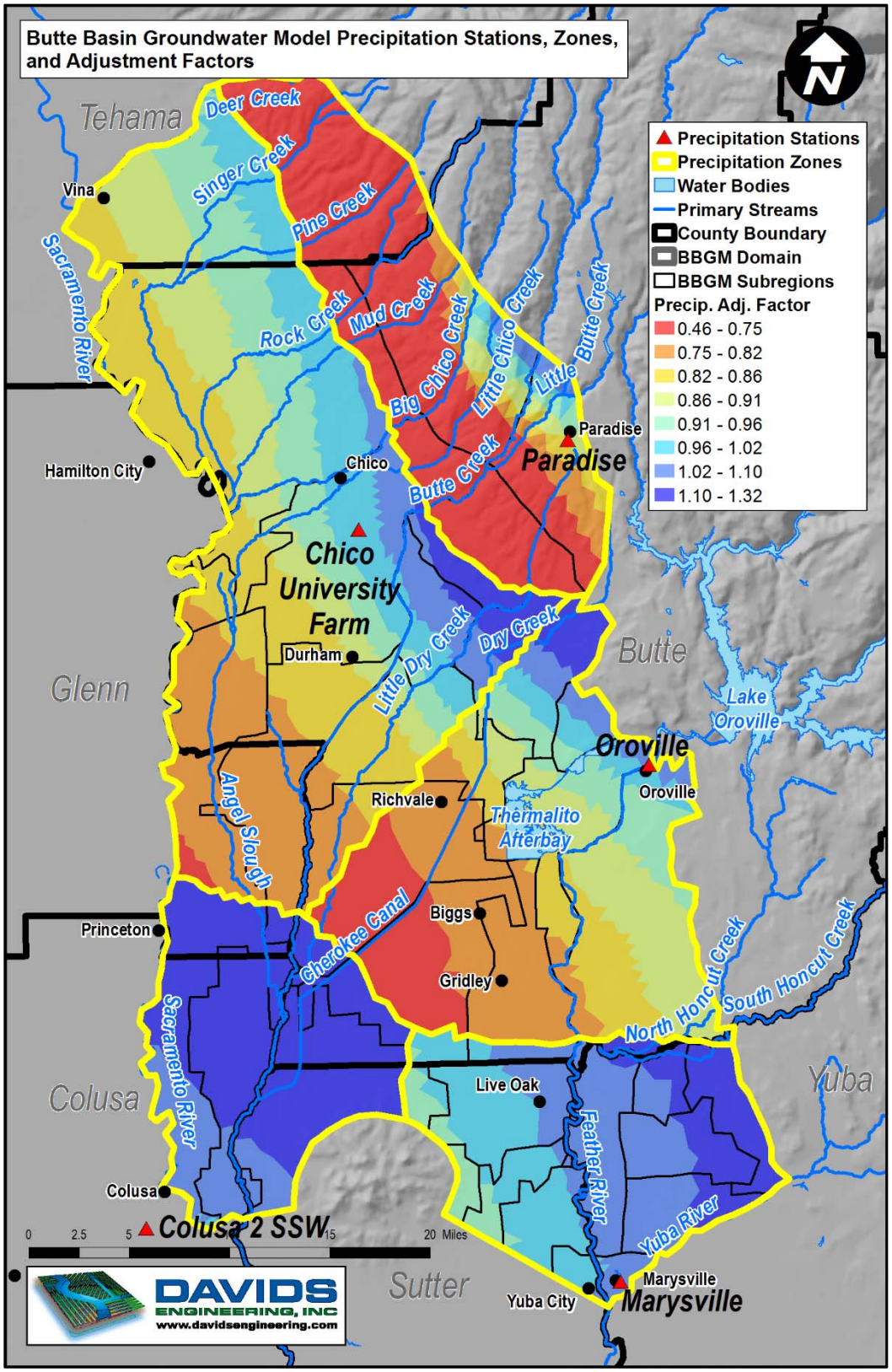

Figure 2.7. Butte Basin Groundwater Model Precipitation Stations, Zones, and Elemental Precipitation Adjustment Factors.

2.3.3 Diversions and Pumping

Diversions

Diversions are estimated based on a combination of available diversion records from water districts, watermaster field schedules, and estimated diversions based on independent estimates of agricultural water demand[4]. The primary surface water users in Butte County divert from Thermalito Afterbay, Butte Creek, and the Sacramento River, and diversion records have been compiled through 2014. Once monthly diversions are estimated, surface water deliveries are calculated as historical diversions minus estimated conveyance losses to spillage, seepage, and evaporation. In the BBGM, diversions occurring from streams represented within the model domain are removed at a specific stream node. Other diversions originating from streams or water bodies for which streamflow is not explicitly modelled are specified to originate outside of the model domain. In either case, diversions for use within the model domain are assigned to the subregion or subregions where the water is used.

Surface water diversions for municipalities, such as Paradise (supplied by Paradise Irrigation District) and Oroville (supplied by California Water Service Company (CalWater)), Thermalito Water and Sewer District (TWSD), and South Feather Water and Power Agency (SFWPA) have been obtained from the water suppliers or estimated based on available Urban Water Management Plans (UWMPs) as part of the BBGM update (West-Yost Associates 2016). For cases in which only annual diversion records are available, representative monthly urban demand patterns have been used to estimate monthly diversions.

Pumping

Groundwater pumping has been estimated for individual subinventory units and aggregated to provide estimates of total pumping for the inventory unit as a whole. Irrigation pumping has been estimated based on cropping, soils, weather conditions, and estimated irrigation efficiencies, similar to surface water diversions for areas known to use surface water but without available diversion records, as described previously. For water suppliers diverting water from Thermalito Afterbay for irrigation (Biggs-West Gridley Water District, Butte Water District, Richvale Irrigation District, and Western Canal Water District) and Gray Lodge Wildlife Area (within the Butte Sink subinventory unit), pumping estimates were developed as part of the Feather River Regional Agricultural Water Management Plan (FRRAWMP) based on estimated areas relying on groundwater within each supplier service area (NCWA 2014). For other areas of the County, the estimates were developed using IDC as part of the BBGM update as the amount of applied water required to meet irrigation or other demands, after accounting for any available surface water deliveries.

[4] As described by HCI (1996), water user areas were developed based on a combination of water source and general land use type (rice, non-rice crops, native vegetation, native riparian) as determined from DWR land use surveys and based on water supplier service areas. For each water user area with a surface water supply but no available diversion records, diversions were estimated based on cropping, soils, weather conditions, and estimated irrigation efficiencies using IDC.

Urban pumping has been estimated based on reported and estimated pumping volumes developed for the BBGM update based on UWMPs, Municipal Service Reviews (MSRs), and the Northern Sacramento Valley Integrated Regional Water Management Plan (NSVIRWMP) (West-Yost Associates 2016). For the City of Chico, monthly pumping volumes were provided for the period of analysis by CalWater. For the City of Oroville, monthly pumping volumes were provided for the period of analysis by CalWater and estimated for TWSD based on the District's UWMP. For the City of Biggs, pumping was estimated based on the City's MSR. For the Durham area, pumping was estimated based on Durham Irrigation District's MSR. For the City of Gridley, pumping was estimated based on the NSVIRWMP. For the Town of Paradise, pumping was based on Paradise Irrigation District's UWMP. For cases in which only annual pumping estimates are available, representative monthly urban demand patterns have been used to estimate monthly pumping. A summary of total pumping per inventory unit is included in Section 4.3.3 under Groundwater Pumping.

Rural residential groundwater pumping has been estimated based on U.S. Census Bureau population estimates and per capita water usage rates for Butte County based on available supplier data described above. Using census data for 2000, the population of areas not within urban water supplier service areas was determined and adjusted over time based on annual County-wide estimates of population. Then, rural residential pumping for each area was estimated assuming demands of approximately 260 gallons per person per day. Estimates of rural residential pumping are summarized in Table 4.3 and in water budgets presented in Section 5.

2.3.4 Land Use

Land use has been estimated annually for each subinventory unit (and groundwater model element) as part of the BBGM update. Data sources for the land use analysis include DWR land use surveys for 1994, 1999, 2004, and 2011 and annual agricultural commissioner crop reports for the full period of analysis. Land use data for the WI&A update were developed as follows:

- Compile available DWR land use surveys and agricultural commissioner crop reports, and assign reported acreages to crop and other land use types represented in the BBGM.
- Intersect the BBGM model elements with the DWR land use surveys in GIS to establish land use within each element at the time of each land use survey.
- For each land use and DWR survey, determine an adjustment factor to be applied to the commissioner crop survey to correct for differences in acreage. Estimate an adjustment factor to be applied to each land use over time by interpolating between land use survey years.
- For each element and land use survey, determine the fraction of total acreage by land use existing within the element. Estimate the fraction to be applied to each element and land use over time by interpolating between land use survey years.

- Apply a special adjustment in years of fallowing based water transfers. In such years, the rice acreage for elements within each participating water district is adjusted based on the estimated amount of land fallowed.
- Aggregate land use for BBGM model elements to subinventory units and inventory units for reporting in the WI&A update.

The approach used to quantify historical land use is generally consistent with the process applied by DWR for the California Water Plan. By utilizing agricultural commissioner crop reports to estimate annual changes in cropping, the approach inherently accounts for economic and other factors that affect annual cropping decisions. Water district-specific accounting for fallowing-based transfers allows for explicit accounting in the BBGM and WI&A update.

Another source of available cropping data is the annual reports of the Joint Districts (BWGWD, RID, BWD, and SEWD). These reports provide annual acreages by general crop type for each of the districts; however, the cropping information is provided at a coarser level of detail than the crop types represented in the BBGM. Additionally, cropping data developed by Western Canal Water District (WCWD) are available. These sources of cropping data were used to validate the cropping information from the DWR crop surveys and agricultural commissioner crop reports.

2.3.5 Reference Evapotranspiration, Crop Coefficients, Actual Evapotranspiration, and Evapotranspiration of Applied Water

Evapotranspiration (ET) by crops and other vegetation represent a primary outflow of water from inventory and subinventory units within the County. For the WI&A and BBGM, ET is estimated for each land use type by multiplying reference evapotranspiration (ETo) by a crop (or water use) coefficient (EToF) as described by Allen et al. (1998). In order to accurately account for ET as part of the water budgets developed for the WI&A, crop coefficients based on actual ET (ETa), as compared to potential ET (ETp) are used. Then, for irrigated crops total ET is partitioned into ET derived from precipitation (ETpr) and ET derived from applied water (ETaw). By dividing ETaw by estimated irrigation efficiencies, estimates of pumping and in some cases surface water diversions are developed.

Reference Evapotranspiration (ETo)

Reference evapotranspiration was estimated based on the California Irrigation Management Information System (CIMIS) agronomic weather station at Durham (Station 12). The Durham station is the only CIMIS station located in Butte County and has a long period of record (established in October 1982). Quality control procedures were applied based on the methodology of Allen et al. (2005). For purposes of the BBGM, ETo prior to 1982 is estimated based on correlation to air temperature using the Hargreaves-Semani equation.

Crop Coefficients (EToF)

Crop coefficients representing actual ET were developed based on available results of a Surface Energy Balance Algorithm for Land (SEBAL) analysis of the Sacramento Valley for 2009 (Bastiaanssen et al. 2005, SNA 2012). Crop coefficients were calculated for each land use class

represented in the BBGM and WI&A update based on actual ET from SEBAL and reference ET from the Durham CIMIS station. For 2009, detailed land use datasets from DWR for Glenn and Colusa counties developed for that year were relied upon to support the analysis.

The SEBAL datasets correspond to the irrigation season from approximately March through September. Crop coefficients during the winter period were estimated using the Basic Irrigation Scheduling (BIS) tool developed by Dr. Richard Snyder at U.C. Davis in cooperation with DWR based on reference ET and precipitation patterns observed during the 2000-2014 update period (Snyder et al. 2007).

A sample SEBAL image depicting actual ET for July 26, 2009 is shown in Figure 2.8. As indicated, data is available for the majority of the County, with the northern edge of the satellite image at approximately Chico.

For almonds and walnuts, crop coefficients during the growing season derived from the 2009 SEBAL data were reduced for prior years based on discussions with University of California Cooperative Extension (UCCE) specialists (Connell and Fulton 2015). Specifically, whereas historical ET for a mature healthy almond orchard was considered to be approximately 42 inches annually in the Sacramento Valley, changes in growing practices since the mid 1990's including tree spacing, pruning practices, fertilization, and irrigation have resulted in estimated ET rates of approximately 48 inches in recent years. As a result of this trend, crop coefficients were reduced linearly from 2010 back to 1995 by approximately one percent per year.

Actual Evapotranspiration (ETa)

Actual evapotranspiration was calculated on a daily basis by multiplying ETo from the Durham CIMIS station by the EToF corresponding to each day and land use type. ETo, crop coefficients, and resulting calculated ETa are shown for 2013 for rice and almonds in Figures 2.9 and 2.10, respectively.

Evapotranspiration of Applied Water (ETaw)

ETaw was calculated on a daily basis for each land use type using the IWFM Demand Calculator (IDC) (DWR 2015). For each day, IDC simulates root zone water balance processes, including precipitation, irrigation, infiltration, runoff, deep percolation, evapotranspiration, and stored soil moisture. Relative amounts of stored soil moisture derived from precipitation and applied irrigation water are tracked over time, and ETa is divided into ETaw and ETpr based on the relative amount of precipitation and applied water each day. For the water budget analysis, daily ETa and ETaw are then aggregated for each inventory and subinventory unit over time.

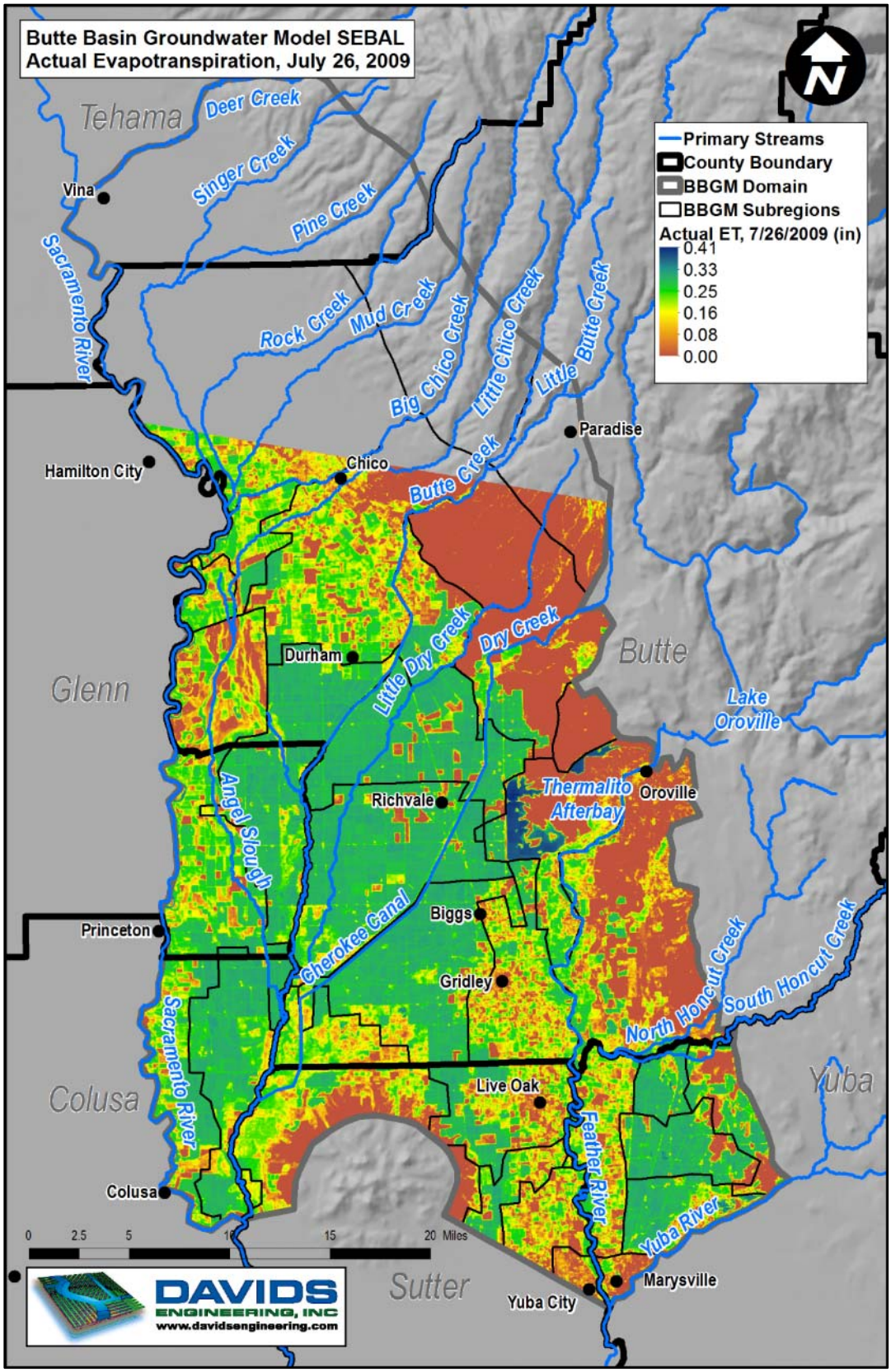

Figure 2.8. Butte Basin Groundwater Model SEBAL Actual Evapotranspiration, July 26, 2009.

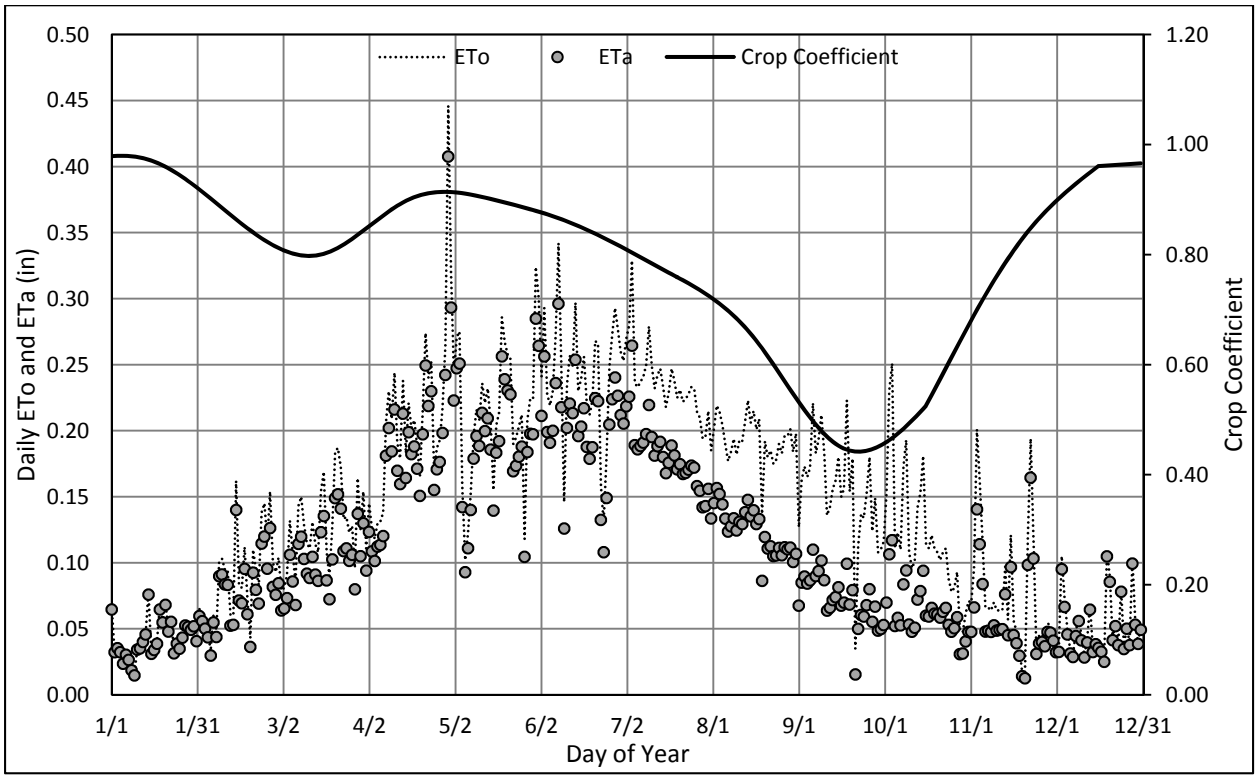

Figure 2.9. Daily Reference ET (ETo), Crop Coefficient (EToF), and Actual ET (ETa) for Almonds, 2013.

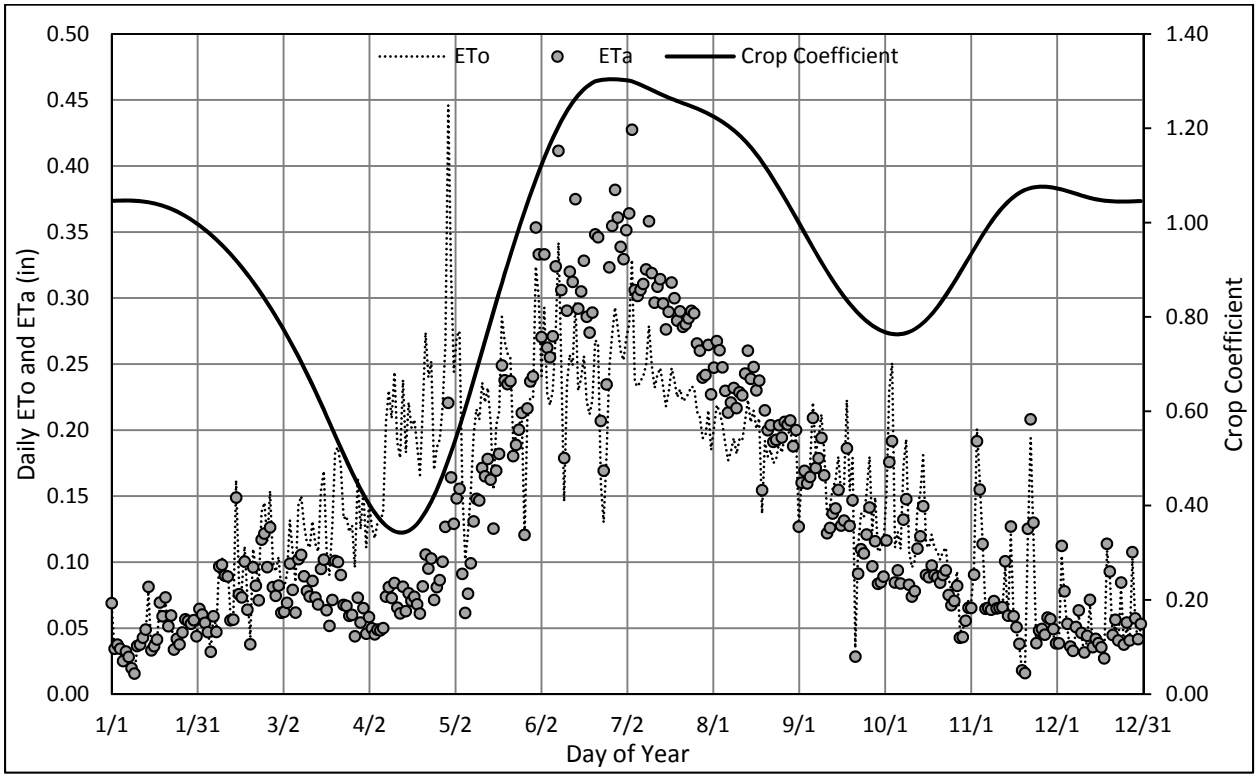

Figure 2.10. Daily Reference ET (ETo), Crop Coefficient (EToF), and Actual ET (ETa) for Rice with Winter Decomp. Water, 2013.

2.3.6 Irrigation Efficiency

Irrigation efficiencies for non-ponded crops (orchards, pasture and hay, and field and annual crops) are parameterized indirectly in IDC by specifying the amount of water to be applied during irrigation events as a fraction of the field capacity of the soil (DWR 2015). Estimated irrigation efficiencies were developed for orchards and other non-ponded crops based on several sources, including discussion with UCCE farm advisors (Connell and Fulton 2015), the project advisory committee, distribution uniformity evaluations conducted by the Tehama County Resource Conservation District (Greer 2013), Canessa et al. (2011), CalFed (2006), and detailed water balances developed as part of the FRRAWMP (NCWA 2014).

Increases in irrigation efficiency for orchards have been observed by UCCE farm advisors over past decades. For purposes of the BBGM and WI&A, irrigation efficiency is expressed as a consumptive use fraction (CUF), calculated as the ratio of ETaw to applied irrigation water on an annual basis. To represent increases in the CUF over time, the target soil moisture fraction (TSMF) was gradually decreased in the BBGM between 1970 and 2010, resulting in an increase in CUF for orchards from around 0.74 in the 1970s to around 0.83 since 2010. Average CUF values by crop are summarized in Table 2.1. These values vary somewhat for a given crop from year to year and based on soil characteristics.

Table 2.1. Average Butte County Consumptive Use Fraction (CUF) Values by Crop, 2000-2014.

Crop Category	Crop	CUF
Rice	with Winter Water	0.51
	without Winter Water	0.59
	Average	0.54
Orchards	Almonds	0.80
	Walnuts	0.79
	Prunes	0.80
	Other	0.65
	Average	0.78
Other Crops	Grain	0.66
	Pasture	0.67
	Other	0.67
	Average	0.67

2.3.7 Land Surface Water Budgets

Land surface water budgets were developed for each valley floor inventory and subinventory unit for the WI&A update period based on the methodology described above and IDC results from the BBGM. They are described in Section 5 and Appendix C. Within each inventory and subinventory unit, an aggregate budget for the area is provided, as well as budgets by general

land use types. Specifically, budgets are provided for irrigated agriculture and wetlands, developed lands, and non-irrigated lands.

Inflows include precipitation, applied surface water (as applicable), and groundwater pumping (as applicable). Outflows include evapotranspiration, surface water runoff and return flows, and deep percolation. Average annual inflows and outflows are presented on a water year basis[5] for the 2000-2014 update period, as well as providing averages for the overall period and by hydrologic water year type.

[5] A water year refers to the period from October to September each year, with the beginning month of October selected based on the typical beginning of the winter rainy season. For example, the 2000 water year includes the period from October 1999 to September 2000.